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Reliability assessment of wind turbine generators by fuzzy universal generating function

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Highlights

- The fuzzy states of the DFIG systems are provided.
- All components' states are given as triangular fuzzy number based on experts' experience.
- The reliability assessment of the DFIG based on the FUGF is performed.

Abstract

Wind power has been widely used in the past decade because of its safety and cleanness. Double fed induction generator (DFIG), as one of the most popular wind turbine generators, suffers from degradation. Therefore, reliability assessment for this type of generator is of great significance. The DFIG can be characterized as a multi-state system (MSS) whose components have more than two states. However, due to the limited data and/or vague judgments from experts, it is difficult to obtain the accurate values of the states and thus it inevitably contains epistemic uncertainty. In this paper, the fuzzy universal generating function (FUGF) method is utilized to conduct the reliability assessment of the DFIG by describing the states using fuzzy numbers. First, the fuzzy states of the DFIG system's components are defined and the entire system state is calculated based the system structure function. Second, all components' states are determined as triangular fuzzy numbers (TFN) according to experts' experiences. Finally, the reliability assessment of the DFIG based on the FUGF is conducted.

Keywords

reliability assessment, double fed induction generator, multi-state system, fuzzy universal generating function.

Acronyms and Abbreviations

DFIG Double Fed Induction Generator
MSS Multi-state System
UGF Universal Generating Function
FUGF Fuzzy Universal Generating Function
TFN Triangular Fuzzy Number
PMG Permanent Magnet Generator
PD Probability Distribution

1. Introduction

Energy is closely connected with our human beings. With the increasing crisis on energy and environmental problems, wind energy has gained significant attention in recent years due to its safety and cleanness. Consequently, technologies related to wind energy developed fast in the past decade. With the increasing capacity of wind turbine generators, wind turbine generator systems are becoming more and more compounded and complicated, especially for the megawatt-scale wind turbine generator systems. For a large complex equipment such as wind turbine generator systems, much attention should be paid to their reliability assessment besides considering their capacity. In general, the designed life span of a wind turbine generator is 20 years. Thus, it is very difficult to have an accurate reliability assessment of the wind turbine.

Due to the external working environments and internal failure dependence, the double fed induction generator (DFIG), as a typical type of wind turbines, inevitably deteriorates with the usage. Once the deterioration beyond the acceptable level, it is deemed as failure. The failure of the DFIG will not only cause energy loss but also create damage to the entire wind farm. Therefore, reliability assessment for the DFIG is of great significance. In the literature, many works on reliability assessment of the DFIG have been reported. Carroll et al [1] studied the reliability of wind turbines with the DFIG and permanent magnet generator (PMG) drive trains. Zhou et al. [34] conducted certain attempts on reliability and performance improvement of the DFIG. Note that most of the existing studies assumed the DFIG system and its components as a binary-state system or components, i.e., the working state and the failure state. However, the DFIG is typically made up of five main components, i.e., blades, gearboxes, generators, converters and transformers. Blades and gearboxes are mechani-

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cal components whose performance rates (levels) degrade with wear. Consequently, there are several intermediate states corresponding to the development of the wear and tear. Furthermore, as electrical parts, generators, converters and transformers still have intermediate states because of the backup. These features indicate that the traditional binary reliability model cannot perfectly characterize the DFIG.

A few works treated the DFIG as a multi-state system (MSS) and the reliability methods for MSS have been widely provided [18, 19, 22, 23]. Eryilmaz [8] presented a reliability method for a MSS with three-state components and applied it into wind energy. Xiao et al. have applied MSS model to many practical problems, and achievements have been made. [31, 32, 33]. UGF are considered as an convenient method for reliability assessment of MSS. Levitin has done a lot of research about UGF [16]. Nevertheless, the uncertainty exists in reliability assessment and cannot be neglected. Due to the limited data and/or vague judgments from experts, obtaining the accuracy value of the performance rates (levels) and probabilities of MSSs are difficult and inevitably contains epistemic uncertainty. Fuzzy set theory can well address the problems caused by the epistemic uncertainty. Huang et al. [11, 12, 13] developed a suit of reliability evaluation algorithms based on the fuzzy set theory. Wu [27] developed a fuzzy Bayesian method and proposed a new method to create the fuzzy Bayes point estimator of reliability. Ding and Lisnianski [6] combined the fuzzy set theory with the UGF technique; then, the fuzzy UGF (FUGF) method was proposed. Liu and Huang [21] further justified the FUGF method and introduced the Markov chain to the FUGF method. Lisnianski et al. [20] proposed an MSS reliability analysis and optimization method based on FUGF. Li et al. [17] provided an improved FUGF method for reliability assessment of MSS under aleatory and epistemic uncertainties. Gao et al. [10] performed dynamic fuzzy reliability analysis for MSS based on UGF. Dong et al. [7] extended the FUGF method for reliability assessment of uncertain MSS. Gao and Zhang [9] proposed a novel reliability analysis method for fuzzy MSS considering correlation based on UGF. The fuzzy theory and reliability analysis of MSS system have also developed recently [15, 24]. Jaiswal et al. [14] proposed Reliability analysis method for non-repairable weighted k-out-of-n system based on belief UGF. Cui et al. [5] presented a reliability model for aircraft actuation system based on power transfer efficiency. Qin et al. [26] proposed a combined method for reliability analysis of MSS of minor-repairable components. Negi and Singh [25] provided the fuzzy reliability evaluation method of linear m-consecutive weighted-k-out-of-r-from-n: F systems. Chen et al. [2] performed the reliability analysis and optimization of equal load-sharing k-out-of-n phased-mission systems.

In this paper, we consider a typical type of wind turbine generator systems, i.e., the DFIG, and model the DFIG as an MSS. As the DFIG is a system with high reliability and few test/event data, traditional reliability assessment methods based on large amount of failure data with rigorous statistical models are incapable of handling such a challenge. Moreover, specifying the component states of the DFIG, such as the states of the blades and gearboxes, often relies on experts' knowledge. Due to the vague judgements of experts, the determination of component states often contains epistemic uncertainty and it is suitable to be modelled as fuzzy numbers [21]. In this work, first, the fuzzy states of the DFIG systems are defined and the entire system state is calculated based on system structure function. Secondly, the performance rates and probabilities of all components' states are determined as triangular fuzzy number (TFN) based on experts' experiences. TFNs are chosen rather than other types of fuzzy numbers due to the easy concept and wide applications to reliability engineering. what's more, if the imprecise component state probability elicited by experts is naturally modelled by the TNFs, the experts only have to decide the most possible values of component state probability and the uncertainty associated with this decision. For other types of fuzzy numbers, such as Trapezoidal fuzzy number, the experts have to decide at least four values associated with the component state probability. It, therefore, introduces additional challenges to the expert elicitation process. Finally, the reliability assessment of the DFIG based on the FUGF is conducted.

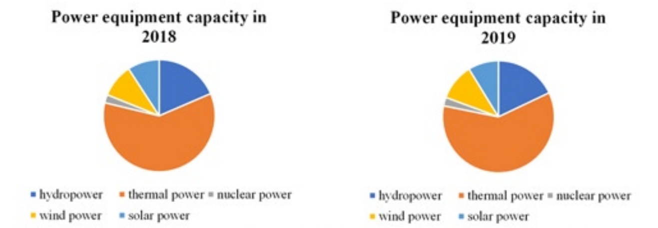
The remainder of this paper is organized as follows. Section 2 introduces a brief overview of the turbine generators. The introduction on the MSS and the UGF are given in Section 3. Section 4 conducts the fuzzy reliability assessment for the DFIG system based on FUGF. Finally, a brief conclusion is given in Section 5.

2. Overview of Wind Turbine Generators

2.1. Background and Structure of Wind Turbine Generators

As a significant new energy, wind power plays an indispensable role in both industry and our daily lives. In China, for example, wind power increases quickly in recent years, and it is ranked the third in the country's power equipment capacity. More information about Chinese power equipment capacity [3, 4] is shown in Fig. 1.

The wind turbine generator is the vital device to convert wind energy into electric energy. According to the output capacity of wind turbine generations, wind turbine generations can be divided into small, medium, large, and megawatt-scale. With the increase of the capacity, double fed wind induction generator (the DFIG) gradually becomes the mainstream of wind turbine generation market due to its good performance and operation stability. As for DFIG, there are five main parts, i.e., the blade, the gearbox, the generator, the converter and the transformer. The structure of DFIG is shown in Fig. 2. The blade can rotate with the wind and then the torque forming. This is the first step that the wind power transforms into mechanical energy. The forming torque will be transmitted to the gearbox for acceleration. The output shaft of gearbox with high-speed rotating is connected with the generator and then the mechanical energy will be transmitted into electric energy. The converter of DFIG is used to excite the rotor of the DFIG. The amplitude, frequency, and phase of the output voltage at the stator side of the DFIG are the same as those of the grid. Without the converter, the generator cannot work normally [30].



Type	Unit	Absolute amount	Increment
Hydropower	MWe	35226	2.5
Thermal power	MWe	114367	3.0
Nuclear power	MWe	4466	24.7
Wind power	MWe	18426	12.4
Solar power	MWe	17463	33.9
Total	MWe	189967	6.5

Type	Unit	Absolute amount	Increment
Hydropower	MWe	35640	1.1
Thermal power	MWe	119500	4.1
Nuclear power	MWe	4874	9.1
Wind power	MWe	21005	14
Solar power	MWe	20468	17.4
Total	MWe	201266	5.8

Fig. 1. Power equipment capacity of China in 2018 and 2019

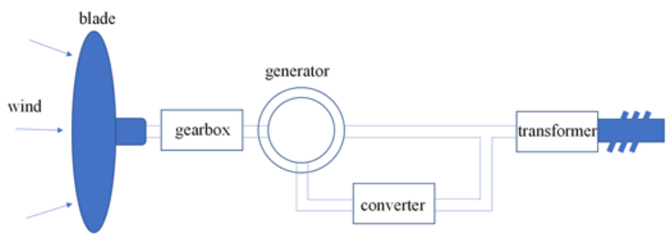


Fig. 2. The structure of DFIG

2.2. Reliability Modeling of a Wind Turbine Generator

According to the physical connections of the five components in DFIG, the reliability block diagram of a DFIG is shown in Fig. 3. In the DFIG, two separate systems with a generator and converter connected in series are used as redundancy. They are connected in series with the blade, the gearbox and the transformer.

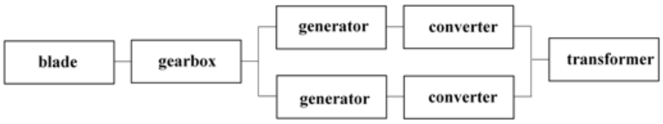


Fig. 3. Reliability block diagram of the DFIG.

The components of a DFIG can be categorized into two types, i.e., the mechanical type and the electrical type. The former includes the blade and the gearbox whose failures are mainly caused by wear. Whereas, the latter includes the generator, the converter and the transformer, whose failures are mainly caused by the damage of IGBT modules. For the former type of components, the mechanical performance will deteriorate into different levels with the development of wear and tear. When the performance reaches a certain threshold, components will be failure. For the latter type of components, the damage of IGBT modules can also make the degradation of performance due to the backup. Therefore, the system of the DFIG can be considered as an MSS whose components have multi-state as well. According to the experts' experiences, the states of every component of the DFIG is defined and given in Table 1. As we can see from Table 1, there are 4 states of blade and gearbox, 3 states of generator, convertor and transformer.

Table 1. States definition of DFIG.

Component	State division
Blade	perfect, mild wear, severe wear, failure (4 states)
Gearbox	perfect, mild wear, severe wear, failure (4 states)
Generator	perfect, middle, failure (3 states)
Converter	perfect, middle, failure (3 states)
Transformer	perfect, middle, failure (3 states)

Based on the structure function of the entire system, there are totally 482 states of the DFIG. Thus, it is difficult to accurately assess the system state parameters and an efficient method for reliability assessment is strongly needed.

3. UGF-Based Reliability Assessment of MSS

3.1. Overview of MSS

For an MSS, it could have a finite number of performance rates (levels). For each component, they could have a finite number of performance rates (levels) as well. In order to conduct the reliability assessment of an MSS, the characteristics of its components should be determined first. Components can have different states with corresponding performance rates (levels). The performance rates (levels) of every states of any components can be represented as:

$$\mathrm{g}_j = \left\{ g_{j1}, \cdots, g_{ji_j}, \cdots, g_{jk_j} \right\}, \tag{1}$$

where i_j indicates $i\text{th}(1 \le i \le k_j)$ state of component and g_{i_j} is the performance rate (level) of j. Then the probabilities associated with different states of component j can be represented as:

$$\mathrm{p}_j = \left\{ p_{j1}, \cdots, p_{ji_j}, \cdots, p_{jk_j} \right\} \tag{2}$$

After determining the performance rates and corresponding probabilities, the probability distribution (PD) of the system can be determined if the system structure function $\phi(\bullet)$ is known. The probability of system state i can be calculated as follows:

$$p_i = \prod_{j=1}^{n} p_{ji_j} \tag{3}$$

The performance rate (level) of MSS for state i is:

$$g_i = \phi(g_{1i_1}, \cdots, g_{ni_n}) \tag{4}$$

The PD of the MSS can be represented as:

$$g_i = \phi(g_{1i_1}, \cdots, g_{ni_n}),\ p_i = \prod_{j=1}^{n} p_{ji_j} \tag{5}$$

3.2. UGF Method

The UGF is an effective method to conduct the reliability assessment of MSSs. Boolean model, stochastic process method, Monte Carlo simulation and UGF method are common method used for reliability analysis of MSS. In engineering practice, the UGF method can be applied to the system with complex structure and function, meanwhile, the calculation is small and the implementation is flexible. Most importantly, reliability assessment via the UGF method can be done by decomposing the calculation of system UGF into a combination of two component UGF. It, therefore, dramatically reduces the computational burden of system reliability assessment for complex systems with many components. As the performance rates and PD of the MSS have been determined, the $z-\text{transform}$ of random variable $\mathrm{g}_j = \{g_{j1}, \cdots, g_{ji_j}, \cdots, g_{jk_j}\}$, $\mathrm{p}_j = \{p_{j1}, \cdots, p_{ji_j}, \cdots, p_{jk_j}\}$ is defined as:

$$u(z) = \sum_{i=1}^{k_j} p_{ji_j} \cdot z^{g_{ji_j}} . \tag{6}$$

Equation (6) represents the PD of the component j. This form is the UGF representation of multi-state component j. The output PD with $z-\text{transform}$ representation of the entire system can be represented as:

$$\begin{aligned} U(\mathrm{z}) &= \Omega_\phi \left\{ u_1(z), \cdots, u_n(z) \right\} \\ &= \Omega_\phi \left\{ \sum_{i_1=1}^{k_1} p_{1i_1} \cdot z^{g_{1i_1}}, \cdots, \sum_{i_n=1}^{k_n} p_{ni_n} \cdot z^{g_{1i_1}} \right\}, \\ &= \sum_{i_1}^{k_1} \sum_{i_2}^{k_2} \cdots \sum_{i_n}^{k_n} \left(\prod_{j=1}^{n} p_{ji_j} \cdot z^{\phi(g_{1i_i}, \cdots, g_{ni_n})} \right) \end{aligned} \tag{7}$$

where Ω_ϕ is a general composition operator. The UGF method is based on the general composition operator and individual universal $z-\text{transform}$ representations. Therefore, the PD of the MSS can be easily obtained through the PDs of each component if the structure function $\phi(\cdot)$ is known. The structure function $\phi(\cdot)$ is defined according to the structure of the system. A system with different structures, such as series, parallel, series-parallel or bridge structures, will have different $\phi(\cdot)$. The states of an MSS can be divided into two subsets depending on whether the state is acceptable by the system function. Whether a state is accepted or not depends on the system demand w. Suppose that the index $r_i : r_i = g_i - w$, the state i is an acceptable state if and only if $r_i \geq 0$. The availability of an MSS is the probability the system staying in the subset of acceptable states:

$$A(w) = \sum_{r_i \geq 0} p_i = \sum_{i=1}^{K} p_i \cdot \alpha_i \,, \tag{8}$$

where:

$$\alpha_i = \begin{cases} 1, \; r_i \geq 0 \\ 0, \; r_i < 0 \end{cases}. \tag{9}$$

Herein, a subsystem of the DFIG is taken as an example to illustrate the UGF-based reliability assessment for MSSs.

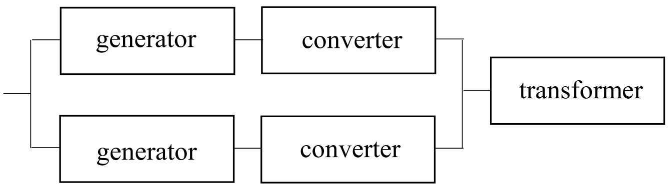


Fig. 4. Structure of the subsystem of DFIG

As shown in Fig. 4, there is a subsystem of DFIG with five components. This subsystem can be treated as a flow transmission system whose performance rate (level) is defined by their transmission capacity. Suppose that there are 3 states of generator (component 1) and converter (component 2) and 2 states of the transformer (component 3). The performance rates (levels) of the states of generator are $g_{11} = 1.7,\ g_{12} = 1.2,\ g_{13} = 0.5$ with the corresponding probabilities being $p_{11} = 0.7,\ p_{12} = 0.2,\ p_{13} = 0.1$, respectively. The performance rates (levels) of the states of the converter are $g_{21} = 0.8,\ g_{22} = 0.2,\ g_{23} = 0$ and the corresponding probabilities are $p_{21} = 0.4,\ p_{22} = 0.3,\ p_{23} = 0.3$. The performance rates (levels) of the states of transformer are $g_{31} = 1,\ g_{32} = 0$ and the corresponding probabilities $p_{31} = 0.5,\ p_{32} = 0.5$. The UGF for each component based on the PD is defined as:

$$u_1(z) = p_{11} \cdot z^{g_{11}} + p_{12} \cdot z^{g_{12}} + p_{13} \cdot z^{g_{13}} = 0.7 \cdot z^{1.7} + 0.2 \cdot z^{1.2} + 0.5 \cdot z^{0.5},$$
$$u_2(z) = p_{21} \cdot z^{g_{21}} + p_{22} \cdot z^{g_{22}} + p_{23} \cdot z^{g_{23}} = 0.4 \cdot z^{0.8} + 0.3 \cdot z^{0.2} + 0.3 \cdot z^{0},$$
$$u_3(z) = p_{31} \cdot z^{g_{31}} + p_{32} \cdot z^{g_{32}} = 0.5 \cdot z^{1} + 0.5 \cdot z^{0}.$$

According to the structure as shown in Figure 4, the system structure function is expressed as:

$$\begin{aligned} &\phi(G_1(t),\ G_2(t),\ G_3(t)) \\ &= \phi_s\left\{\phi_p\left[\phi_s(G_1(t),\ G_2(t)), \phi_s(G_1(t),\ G_2(t))\right], G_3(t)\right\} \\ &= \min\left\{\left[\min(G_1(t),\ G_2(t)) + \min(G_1(t),\ G_2(t))\right], G_3(t)\right\} \end{aligned},$$

and the PD of the entire system can be obtained as:

$$\begin{aligned} &\Omega_\phi(u_1(z),\ u_2(z),\ u_3(z)) \\ &= \Omega_{\phi s}\left\{\Omega_{\phi p}\left[\Omega_{\phi s}(u_1(t),\ u_2(t)), \Omega_{\phi s}(u_1(t),\ u_2(t))\right], u_3(t)\right\} \\ &= \Omega_{\phi s}\begin{Bmatrix} 0.1296 \cdot z^{1.6} + 0.0288 \cdot z^{1.3} + 0.2176 \cdot z^{1} + 0.216 \cdot z^{0.8} + 0.024 \cdot z^{0.7} \\ +0.024 \cdot z^{0.5} + 0.09 \cdot z^{0.4} + 0.18 \cdot z^{0.2} + 0.09 \cdot z^{0}, 0.5 \cdot z^{1} + 0.5 \cdot z^{0} \end{Bmatrix} \\ &= 0.188 \cdot z^{1} + 0.108 \cdot z^{0.8} + 0.012 \cdot z^{0.7} + 0.012 \cdot z^{0.5} + 0.045 \cdot z^{0.4} + 0.09 \cdot z^{0.2} + 0.545 \cdot z^{0} \end{aligned}.$$

Therefore, the system availability is calculated as:

$$\begin{aligned} A(0.5) &= \sum_{i=1}^{4} \mathrm{p_i} \cdot \alpha_i = 0.188 + 0.108 + 0.012 + 0.01 \\ &= 0.32 \end{aligned}.$$

The result of 0.32 can be considered as the system availability corresponding to the demand w =0.5, and the reliability of the system can be assessed if the reliability demand is a set.

4. FUGF Method for Reliability Assessment of the DFIG

4.1. FUGF

Fuzzy reliability theory is a combination of fuzzy mathematics and reliability theory. Conventional UGF technique is based on two fundamental assumptions. Firstly, the probabilities of each state of each component can be fully characterized by probability measures. Secondly, the performance rate of each component can be precisely determined. However, since the performance rates and probabilities cannot be obtained precisely in practical engineering, the FUGF technique is developed. Therefore, the values in UGF cannot be represented as crisp numbers and the values can be considered around a crisp number. In this situation, the fuzzy set and fuzzy number are proposed to describe such epistemic uncertainty.

A fuzzy number is different from a crisp number because it is a subset defined by its membership function. For example, $\tilde{X}$ is a fuzzy subset, and is defined by its membership function $\mu_{\overline{X}}(x): U \rightarrow [0,1]$. The values of $\mu_{\overline{X}}(x)$ are in the range of 0 to 1, and the value of $\mu_{\overline{X}}(x)$ indicates the probability that the fuzzy number can be obtained as a specific value x . There are different kinds of fuzzy numbers with different kind of membership functions. In this paper, the TFN is considered. The membership function of a typical TFN parameterized by the triplet is defined as:

$$\mu_{\overline{X}}(x) = \begin{cases} \dfrac{x-a}{b-a}, & a \leq x \leq b \\ 1, & x = b \\ \dfrac{x-c}{b-c}, & b < x \leq c \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

And the function can be plotted as Fig. 5.

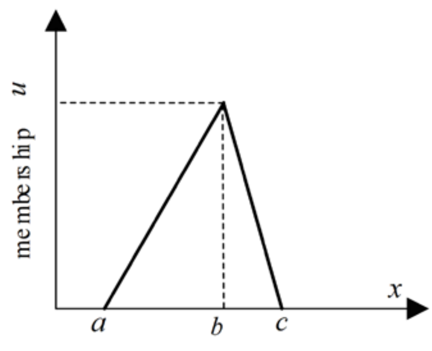


Fig. 5. Membership function of TFN

If fuzzy values exist in the UGF, it can be considered as FUGF. In this paper, both the performance rates and the probabilities are treated as fuzzy numbers. Furthermore, all the fuzzy numbers in this paper are considered as TFNs.

For a fuzzy MSS with n components, the component $j(1 \leq j \leq n)$ can have k_j different states, the corresponding PD can be represented as ordered fuzzy sets $\tilde{\mathrm{g}}_\mathrm{j} = \left\{\tilde{g}_{j1}, \cdots, \tilde{g}_{ji_j}, \cdots, \tilde{g}_{jk_j}\right\}$ and

$\tilde{\mathrm{p}}_{\mathrm{j}} = \left\{ \tilde{p}_{j1}, \cdots, \tilde{p}_{ji_j}, \cdots, \tilde{p}_{jk_j} \right\}$, so the fuzzy performance rates (levels) and probabilities of each state are:

$$\begin{cases} \tilde{p}_{ji_j} = \left\{ p_{ji_j}, \mu_{\tilde{p}_{ji_j}}(p_{ji_j}) \mid p_{ji_j} \in P_{ji_j} \right\} \\ \tilde{g}_{ji_j} = \left\{ \tilde{g}_{ji_j}, \mu_{\tilde{g}_{ji_j}}(g_{ji_j}) \mid g_{ji_j} \in G_{ji_j} \right\} \end{cases} \tag{11}$$

where $\mu_{\tilde{p}_{ji_j}}$ and $\mu_{\tilde{g}_{ji_j}}$ are membership function of $\tilde{p}_{ji_j}$ and $\tilde{g}_{ji_j}$, P_{ji_j} and G_{ji_j} are collection of objects denoted by $\tilde{p}_{ji_j}$ and $\tilde{g}_{ji_j}$, respectively.

The operation of fuzzy number follows the extension principle, the performance of system state i can be evaluated as:

$$\begin{aligned} \tilde{g}_i &= \tilde{\phi}(\tilde{g}_{1i_1}, \cdots \tilde{g}_{ji_j}, \cdots, \tilde{g}_{ni_n}) \\ &= \left\{ g_i, \mu_{\tilde{g}_i}(g_i) \mid g_i = \phi(g_{1i_1}, \cdots, g_{ji_j}, \cdots, g_{ni_n}), g_{ji_j} \in G_{ji_j} \right\} \end{aligned} \tag{12}$$

where $\mu_{\tilde{g}_i}(g_i) = \sup_{\phi(g_{1i_1}, \cdots, g_{ji_j}, \cdots, g_{ni_n})} \min\left\{ \mu_{g_{1i_1}}, \cdots, \mu_{g_{ji_j}} \right\}$, and $\phi(g_{1i_1}, \cdots, g_{ji_j}, \cdots, g_{ni_n})$ is the structure function of FMSS.

The probability of system state i represented by fuzzy numbers can be calculated as:

$$\tilde{p}_i = \left\{ p_i, \mu_{\tilde{p}_i}(p_i) \mid p_i = \prod_{j=1}^{n} p_{ji_j}, p_{ji_j} \in P_{ji_j} \right\} \tag{13}$$

where $\mu_{\tilde{p}_i}(p_i) = \sup_{p_i = \prod_{j=1}^{n} p_{ji_j}} \min\left\{ \mu_{p_{1i_1}}, \cdots, \mu_{p_{ji_j}} \right\}$.

The PD of a FMSS can be calculated as:

$$\begin{aligned} U(z) &= \Omega_{\phi}\left(\sum_{i_1=1}^{k_1} \tilde{p}_{1i_1} \cdot z^{\tilde{g}_{1i_1}}, \cdots, \sum_{i_n=1}^{k_n} \tilde{p}_{ni_n} \cdot z^{\tilde{g}_{1i_1}} \right) \\ &= \sum_{i_1}^{k_1} \sum_{i_2}^{k_2} \cdots \sum_{i_n}^{k_n} \left(\tilde{p}_i \cdot z^{\phi(\tilde{g}_{1i_1}, \cdots, \tilde{g}_{ni_n})} \right) \\ &= \sum_{i_1}^{k_1} \sum_{i_2}^{k_2} \cdots \sum_{i_n}^{k_n} \left(\tilde{p}_i \cdot z^{\tilde{g}_i} \right). \end{aligned} \tag{14}$$

Since system demand is represented as a fuzzy number, the availability assessment for a fuzzy MSS is re-defined in this paper. If the performance rate (level) g for the state i is represented as a TFN parameterized by a triplet (a, b, c) and the system demand w is represented as a TFN parametrized by a triplet (x, y, z), there would be different kinds of relationship between them.

If $a \geq x$, state i is a reliable state.

If $x \geq c$, state i is a failure state.

If there is an overlapping between (a, b, c) and (x, y, z), $|ar_i|_{\mathrm{rel}}$ is defined to obtain the availability. The availability of a FMSS can be represented as:

$$\tilde{A}(\tilde{w}) = \sum_{I=I}^{k} \tilde{p}_i \cdot |ar_i|_{\mathrm{rel}}, \tag{15}$$

where $|ar_i|_{\mathrm{rel}}$ is the relative cardinality of fuzzy set $\tilde{ar_i}$ and $\tilde{ar_i} = \left\{ ar_i, \mu(ar_i) \mid \mu(ar_i) = \mu(r_i), ar_i \in AR_i \right\}$. $|ar_i|_{\mathrm{rel}}$ can be obtained by the following equations:

$$\begin{cases} |r_i| = \sum_{r_i \in R_i} \mu_{\tilde{r}_i}(r_i) \\ |ar_i| = \sum_{ar_i \in AR_i} \mu_{\tilde{ar_i}}(ar_i) \\ |ar_i|_{\mathrm{rel}} = |ar_i| / |r_i| \end{cases} \tag{16}$$

where $|ar_i|_{\mathrm{rel}}$ is the relative cardinality of fuzzy set $\tilde{ar_i}$, and $AR_i = \left\{ r_i \in R \mid r_i \geq 0 \right\}$, $\tilde{ar_i} = \left\{ ar_i, \mu(ar_i) \mid \mu(ar_i) = \mu(r_i), ar_i \in AR_i \right\}$.

4.2. Reliability Assessment of the DFIG by FUGF

From the state definitions of DFIG in Table 1, there are 4 states of the blade and the gearbox, and 3 states of the generator, the converter and the transformer, respectively. The degradation forms of components are different, for instance, the blade will have a slower speed of rotation but the gearbox will have a lower speed of the output shaft during degradation. Due to limited reliability testing resources (e.g., time, budget, manpower), the amount of collected reliability-related data from the components of the DFIG are extremely small. It, therefore, becomes difficult to estimate the precise values of the state probabilities of the DFIG and its components [28], [29]. Alternatively, imprecise information with respect to the DFIG and its components states, i.e., the performance rates (levels), and the corresponding state probabilities can be gathered from experts. In this work, the performance rates (levels) of all components are treated as TFNs under the fuzzy set theory, as tabulated in Table 2. The data in Table 2 are collected from real industry according to cooperation with wind turbine enterprises.

Based on the given values, the reliability assessment based on FUGF can be conducted as follows:

$$\begin{aligned} u_1(z) &= \tilde{p}_{11} \cdot z^{\tilde{g}_{11}} + \tilde{p}_{12} \cdot z^{\tilde{g}_{12}} + \tilde{p}_{13} \cdot z^{\tilde{g}_{13}} + \tilde{p}_{14} \cdot z^{\tilde{g}_{14}} = (0.72, 0.76, 0.77) \cdot z^1 \\ &\quad + (0.1, 0.11, 0.13) \cdot z^{(0.7, 0.8, 0.85)} + (0.06, 0.08, 0.1) \cdot z^{(0.45, 0.5, 0.6)} + (0.03, 0.05, 0.06) \cdot z^0, \\ u_2(z) &= \tilde{p}_{21} \cdot z^{\tilde{g}_{21}} + \tilde{p}_{22} \cdot z^{\tilde{g}_{22}} + \tilde{p}_{23} \cdot z^{\tilde{g}_{23}} + \tilde{p}_{24} \cdot z^{\tilde{g}_{24}} = (0.71, 0.72, 0.75) \cdot z^1 \\ &\quad + (0.2, 0.21, 0.23) \cdot z^{(0.75, 0.78, 0.8)} + (0.03, 0.05, 0.08) \cdot z^{(0.35, 0.4, 0.48)} + (0.01, 0.02, 0.03) \cdot z^0, \\ u_3(z) &= \tilde{p}_{31} \cdot z^{\tilde{g}_{31}} + \tilde{p}_{32} \cdot z^{\tilde{g}_{32}} + \tilde{p}_{33} \cdot z^{\tilde{g}_{33}} = (0.77, 0.83, 0.86) \cdot z^1 \\ &\quad + (0.12, 0.15, 0.2) \cdot z^{0.7} + (0.02, 0.06, 0.09) \cdot z^0, \\ u_4(z) &= \tilde{p}_{41} \cdot z^{\tilde{g}_{41}} + \tilde{p}_{42} \cdot z^{\tilde{g}_{42}} + \tilde{p}_{43} \cdot z^{\tilde{g}_{43}} = (0.81, 0.87, 0.92) \cdot z^1 \\ &\quad + (0.04, 0.1, 0.12) \cdot z^{0.6} + (0.01, 0.03, 0.06) \cdot z^0, \\ u_5(z) &= \tilde{p}_{51} \cdot z^{\tilde{g}_{51}} + \tilde{p}_{52} \cdot z^{\tilde{g}_{52}} + \tilde{p}_{53} \cdot z^{\tilde{g}_{53}} = (0.76, 0.82, 0.84) \cdot z^1 \\ &\quad + (0.11, 0.13, 0.17) \cdot z^{0.55} + (0.03, 0.05, 0.08) \cdot z^0. \end{aligned}$$

According to Fig. 3, components 3 and 4 are connected in parallel. Therefore, the operator $\tilde{\Omega}_{\tilde{\phi}_{\mathrm{P}}}$ is applied between $u_1(z)$ and $u_2(z)$:

$$\begin{aligned} &\tilde{\Omega}_{\tilde{\phi}_{\mathrm{s}}}(u_3(z), u_4(z)) \\ &= (0.6237,\ 0.7221,\ 0.7912) \cdot z^1 + (0.0972,\ 0.1305,\ 0.1840) \cdot z^{0.7} \\ &+ (0.0356,\ 0.0980,\ 0.1272) \cdot z^{0.6} + (0.0261,\ 0.0878,\ 0.1626) \cdot z^0 \\ &\tilde{\Omega}_{\tilde{\phi}_P}[\tilde{\Omega}_{\tilde{\phi}_{\mathrm{s}}}(u_3(z), u_4(z)), \tilde{\Omega}_{\tilde{\phi}_{\mathrm{s}}}(u_3(z), u_4(z))] \\ &= (0.3890,\ 0.5214,\ 0.6260) \cdot z^2 + (0.1212,\ 0.1884,\ 0.2912) \cdot z^{1.7} \\ &= (0.0444,\ 0.1416,\ 0.2012) \cdot z^{1.6} + (0.0094,\ 0.0170,\ 0.0339) \cdot z^{1.4} \\ &= (0.0070,\ 0.0256,\ 0.0468) \cdot z^{1.3} + (0.0013,\ 0.0096,\ 0.0162) \cdot z^{1.2} \\ &= (0.0326,\ 0.1268,\ 0.2572) \cdot z^1 + (0.0050,\ 0.0230,\ 0.0598) \cdot z^{0.7} \\ &= (0.0018,\ 0.0172,\ 0.0414) \cdot z^{0.6} + (0.0007,\ 0.0077,\ 0.0264) \cdot z^0 \end{aligned}$$

Table 2. Performance rates and probabilities of each component of DFIG

Component (No.)	State (No.)	Performance rate	Probability
Blade (1)	Perfect (11)	1	(0.72, 0.76, 0.77)
	mild wear (12)	(0.7, 0.8, 0.85)	(0.1, 0.11, 0.13)
	severe wear (13)	(0.45, 0.5, 0.6)	(0.06, 0.08, 0.1)
	Failure (14)	0	(0.03, 0.05, 0.06)
Gearbox (2)	Perfect (21)	1	(0.71, 0.72, 0.75)
	mild wear (22)	(0.75, 0.78, 0.80)	(0.20, 0.21, 0.23)
	severe wear (23)	(0.35, 0.4, 0.48)	(0.03, 0.05, 0.08)
	Failure (24)	0	(0.01, 0.02, 0.03)
Generator (3)	Perfect (31)	1	(0.77, 0.83, 0.86)
	Middle (32)	0.7	(0.12, 0.15, 0.2)
	Failure (33)	0	(0.02, 0.06, 0.09)
Converter (4)	Perfect (41)	1	(0.81, 0.87, 0.92)
	Middle (42)	0.6	(0.04, 0.1, 0.12)
	Failure (43)	0	(0.01, 0.03, 0.06)
Transformer (5)	Perfect (51)	1	(0.76, 0.82, 0.84)
	Middle (52)	0.55	(0.11, 0.13, 0.17)
	Failure (53)	0	(0.03, 0.05, 0.08)

The FUGF of the entire system can be obtained as follows:

$$\tilde{\Omega}_S = \tilde{\Omega}_{\tilde{\phi}_S}\left\{u_1(z),\, u_2(z),\, \tilde{\Omega}_{\tilde{\phi}_P}[\tilde{\Omega}_{\tilde{\phi}_S}(u_3(z),\, u_4(z)),\tilde{\Omega}_{\tilde{\phi}_S}(u_3(z),\, u_4(z))],\, u_5(z)\right\} = \sum_{i=1}^{432}\tilde{p}_i \cdot z^{\tilde{g}_i}$$

Since there are 432 states of the DFIG system, it is difficult to list all the states. Thus, the successful states are considered to conduct the availability assessment. Let $\tilde{\Omega}_S$ be the FUGF of the acceptable states with the system demand is $(0.78,\ 0.85,\ 0.92)$, then we have:

$$\tilde{\Omega}_S = (0.2350, 0.4623, 0.7143)\cdot z^1 + (0.0326, 0.0669, 0.1206)\cdot z^{(0.8,\ 0.83,\ 0.85)}$$

$$|\,ar_2\,|_{\text{rel}} = 1/7 = 0.1429$$

$$\tilde{A}(\tilde{w}) = (0.2350, 0.4623, 0.7143) + (0.0326, 0.0669, 0.1206) * 0.1429 = (0.2397, 0.4719, 0.7315)$$

5. Conclusions

In this paper, the reliability assessment of the DFIG, a typical wind turbine generator, is conducted under the fuzzy set theory. The DFIG, which consists of a blade, a gearbox, a generator, a converter, and a transformer is treated as an MSS. The FUGF method is used to evaluate the reliability of the DFIG with fuzzy states and probabilities. Firstly, the reliability block diagram of DFIG is built according to the system structure function. Secondly, the component states are defined. Specifically, there are four (perfect, mild wear, severe wear and failure) states for the blade, 4 states (perfect, mild wear, severe wear and failure) for the gearbox, 3 states (perfect, middle and failure) for the generator, 3 states (perfect, middle and failure) for the converter, and 3 states (perfect, middle and failure) for transformer. Finally, the FUGF method is used to calculate the fuzzy availability of the entire DFIG system based on the reliability block diagram, fuzzy states and the corresponding probabilities. The results show that given the system demand $(0.78,\ 0.85,\ 0.92)$, the availability of the DFIG system is $(0.2397,\ 0.4719,\ 0.7315)$. If the system demand increases to a higher level, the availability of system will decrease and vice versa. Triangular fuzzy number is a special category of trapezoidal fuzzy number, which is the most widely studied fuzzy number. Most fuzzy concepts and fuzzy information in real life, especially some fuzzy judgments of decision-makers or experts' experience, can be expressed by triangular fuzzy numbers. It is noteworthy that the proposed constrained optimization model for reliability assessment is not restricted to the TNF. It can be readily implemented to other types of fuzzy numbers because at any cut levels, we can find the interval of the component state probability of any type of fuzzy numbers. Therefore, the proposed method is a generalized method for reliability assessment under fuzzy set theory. However, for reliability assessment of MSS, UGF method is convenient, but it is not equal to that UGF method is the most accurate one. In the future, we need to further compare the accuracy of the results with other methods. This is the direction we will focus on in the future.

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